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Electromagnetic Pulses at Short-Pulse Laser Facilities

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Abstract. Electromagnetic Pulse (EMP) is a known issue for short-pulse laser facilities, and will also be an issue for experiments using the advanced radiographic capability (ARC) at the National Ignition Facility (NIF). The ARC diagnostic uses four NIF beams that are compressed to picosecond durations for backlighting ignition capsules and other applications. Consequently, we are working to understand the EMP due to high-energy (MeV) electrons escaping from targets heated by short-pulse lasers. Our approach is to measure EMP in the Titan short-pulse laser at Lawrence Livermore National Laboratory (LLNL) and to employ that data to establish analysis and simulation capabilities. We have installed a wide variety of probes inside and outside the Titan laser chamber. We have high-frequency B-dot and D-dot probes, a photodiode, and fast current-viewing and integrating current transformers. The probe outputs are digitized by 10 and 20 Gsample/s oscilloscopes. The cables and oscilloscopes are well shielded to reduce noise. Our initial measurement campaign has yielded data useful mainly from several hundreds of MHz to several GHz. We currently are supplementing our high-frequency probes with lower-frequency ones to obtain better low-frequency data. In order to establish analysis and simulation capabilities we are modeling the Titan facility using various commercial and LLNL numerical electromagnetics codes. We have simulated EMP generation by having a specified number of electrons leave the target and strike the chamber wall and other components in the chamber. This short impulse of electrons has a correspondingly broad spectrum, exciting high-frequency structure in the resulting EMP. In this paper, we present results of our initial measurement campaign and comparisons between the measurements and simulations.

1. Introduction

Electromagnetic pulses (EMP) are generated in all laser facilities. For lasers with nanosecond-long pulses, laser plasma interactions can produce “hot electrons” in the 10 to 100 keV range. The number of these hot electrons is usually inferred from the hard x-rays produced when these electron interact with the target material. A fraction of these “hot electrons” can escape prior to the building up of an electrostatic field associated with the escaping electrons that limits the number of additional escaping electrons. It is believed that a significant source of EMP in these systems is due to the escaping electrons. The level of EMP is generally the greatest for large targets, with a potential reason being a reduced electrostatic field associated with the larger surface area allowing more electrons to escape. There are a number of questions on how EMP will scale with laser energy, pulse duration, and target size, going from existing lasers to NIF and the Laser MegaJoule (LMJ) facilities. In addition, NIF will have short pulses (picosecond) on 4 beams as part of the advanced radiographic capability (ARC) for backlighting ignition capsules and other applications. At short-pulse laser facilities, EMP is known to

be an important issue and shielding of components has not been always successful [1]. In general, short-pulse lasers produce very energetic (MeV) electrons and because of their high energy more can escape from the target. Even in the case of short-pulse lasers, the number of electrons that escape ($\sim 10^{12}$) is a small fraction of the total number produced in the target, and the associated charge is a small fraction of a Coulomb. However, the short duration can produce very large transient currents and large EMP. In addition, the short impulse of electrons has a correspondingly broad spectrum with the potential of high-frequency EMP. For effective shielding it is critical that the frequency of the EMP is known. The presence of small-scale structure in laser chambers contributes to the fraction of the EMP that is at higher frequencies. Mitigation of EMP also requires simulation capabilities. We have fielded many different diagnostics in the Titan short-pulse laser [2], which is a part of the Jupiter Laser Facility at LLNL, in order to obtain data necessary to establish analysis and simulation capabilities. The Titan shots that we are measuring have approximately one-twentieth of the energy of ARC (200 J versus 4 kJ), but have approximately the same intensity and pulse length (in the pico-second regime).

2. Measurement campaign

As a part of our 2006 and 2007 measurement campaign in Titan, we have fielded a wide variety of diagnostics in order to understand EMP inside short-pulse lasers. We employ a photodiode to discern the arrival of the laser pulse. We have high-frequency B-dot probes both inside and outside the laser chamber and D-dot probes inside to measure the levels of electromagnetic fields. (It is important to measure both the time varying magnetic and electric fields because the ratio of the fields generally is not the free-space value inside resonant chambers.) We have fast current-viewing and integrating current transformers monitoring a Faraday cup so that we can obtain estimates of the number of high-energy (MeV) electrons escaping from targets. The probe outputs are digitized by 10 and 20 Gsample/s oscilloscopes. The cables and oscilloscopes are well shielded to reduce noise. Figure 1 displays a truncated version of one of the signals obtained from our high-frequency B-dot probe after deconvolution of the probe transfer function. The deconvolution is performed using an optimal method based on the Wiener solution with a regularization parameter [3]. Figure 1 also displays a one-sided spectral estimate of the deconvolved signal. Some of the major peaks in the noise floor probably are oscilloscope artifacts. Note the broad spectrum in the measured EMP, due to the short impulse of electrons. Note also that we do not see identifiable peaks around the low-frequency resonance modes of the chamber (~ 100 MHz). This possibly is a result of the attenuation of the low-frequency portion of the signal, relative to the high-frequency portion, by the differentiating characteristic of the B-dot probe. This attenuation could force the low-frequency signals to be close to or below the oscilloscope noise floor. Thus, our initial measurement campaign has yielded data useful mainly from several hundreds of MHz to several GHz. We currently are supplementing our high-frequency probes with lower-frequency ones, such as depicted in [1, 4], to obtain better low-frequency data. We are also exploring analog filtering and signal processing methods to enhance the low-frequency data.

We are using image plates to determine the spatial distribution of the escaping electrons. For some laser/targets conditions, we have observed a high energy beam of electrons escaping from the backside of a thin target. The electrons generating the image shown in Figure 2 had energies greater than 1 MeV in order to penetrate a 3-mm thick Al plate that was placed in front of the image plate. We will use measured distributions of escaping electrons as inputs to our electromagnetic simulation codes.

3. Simulations

An essential part of understanding EMP in short-pulse lasers is to establish predictive capabilities so that the EMP can be characterized beforehand and mitigation techniques developed without further experiments. We have simulated EMP generation by having a specified number of electrons leave the target and strike the chamber wall using EMSolve [5], a numerical electromagnetics code developed at LLNL. Figure 3 displays frames of a time sequence of a simulation of 10^{12} electrons in a Gaussian

bunch with a full-width at half maximum of 100 ps. The electron bunch is propagating away from the target positioner, as if a short-pulse laser has just struck the target. Figure 4 shows a sample time-series trace of the magnetic field within the chamber. Figure 4 also depicts one-sided spectral estimates of the time-series trace, with the B-field values linearly scaled for different numbers of electrons. The short impulse of electrons in this simulation excites a correspondingly broad spectrum, as is observed in a qualitative comparison with the measured data in Figure 1.

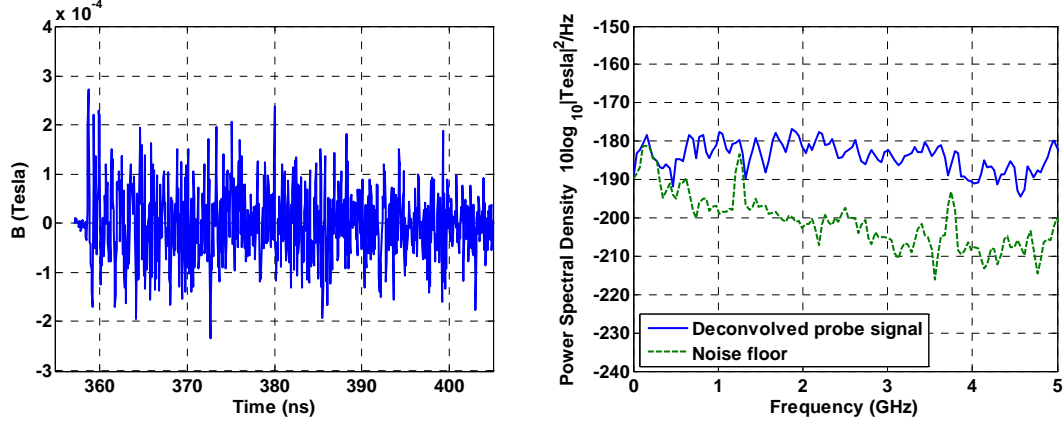


Figure 1: High-frequency B-dot probe signal and one-sided power spectral density estimate after deconvolution of probe transfer function.

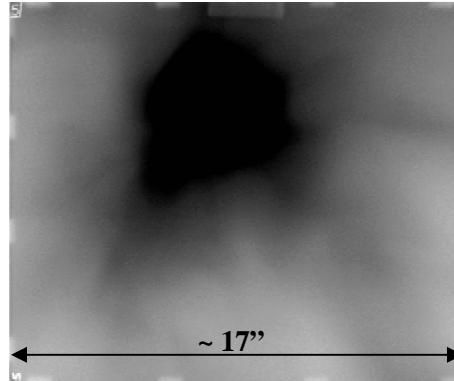


Figure 2: Spatial distribution of a high-energy beam of electrons, observed using an image plate.

4. Conclusions

EMP is a known issue for short-pulse laser facilities. It will also be an issue for experiments using ARC at NIF. We are working to understand the EMP due to high-energy (MeV) electrons escaping from targets heated by short-pulse lasers by measuring and simulating EMP in Titan. We are measuring EMP in Titan using a wide variety of diagnostics. We can simulate EMP due to electrons generated by laser-plasma interactions. Such simulations can provide insight into the mechanisms and characteristics of EMP in short-pulse laser facilities and into possible mitigation methods, without further experiments.

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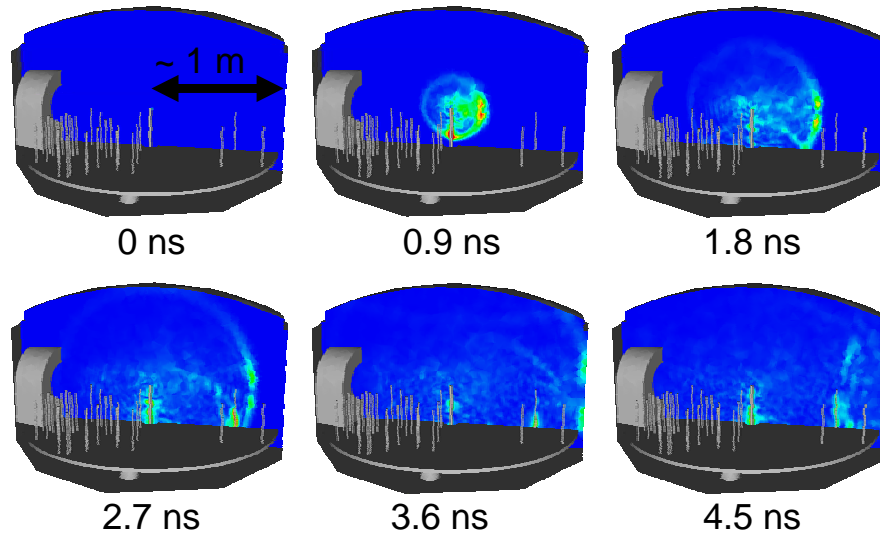


Figure 3: Time sequence of a simulation of the magnetic field due to a bunch of electrons propagating away from the laser target.

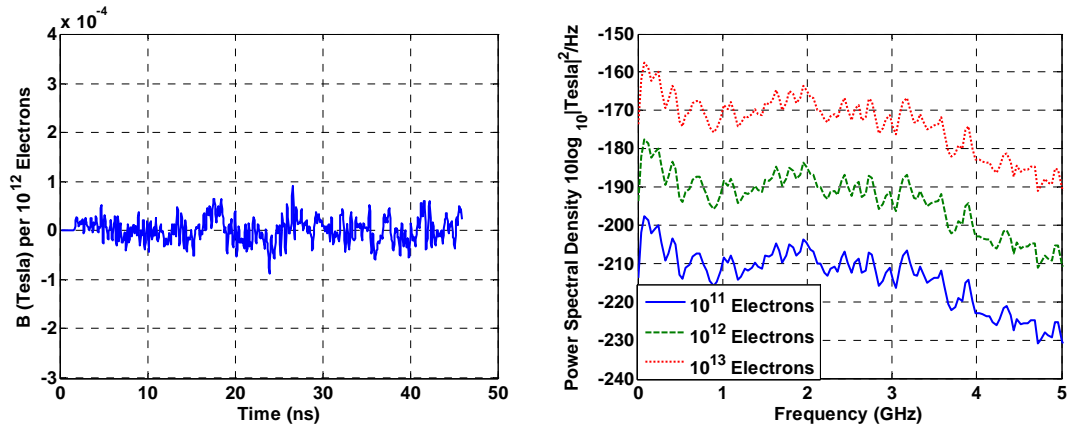


Figure 4: Sample of the magnetic field within an electromagnetic simulation of an electron bunch propagating in the Titan chamber. Also depicted are one-sided power spectral density estimates.

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